Influence of Within-Orchard Trap Placement on Catch of Codling Moth (Lepidoptera: Tortricidae) in Sex Pheromone–Treated Orchards

A. L. KNIGHT[1]

Yakima Agricultural Research Laboratory, USDA–ARS, 5230 Konnowac Pass Road, Wapato, WA 98951

Environ. Entomol. 36(2): 425–432 (2007)

ABSTRACT The influence of trap placement on catches of codling moth, *Cydia pomonella* L., was examined in a series of studies conducted in orchards treated with Isomate-C Plus sex pheromone dispensers. Mark–recapture tests with sterilized moths released along the interface of pairs of treated and untreated apple and pear plots found that significantly more male but not female moths were recaptured on interception traps placed in the treated plots. In a second test, significantly higher numbers of wild male and female moths were caught on interception traps placed in treated versus untreated plots within a heavily infested orchard. The highest numbers of male moths were caught on traps placed along the interior edge of the treated plots. Trap position had no influence on the captures of female moths. In a third test, north–south transects of sex pheromone–baited traps were placed through adjacent treated and untreated plots that received a uniform release of sterilized moths. Traps on the upwind edge of the treated plots caught similar numbers of moths as traps upwind from the treated plots. Moth catch was significantly reduced at all other locations inside versus outside of the treated plots, including traps placed on the downwind edge of the treated plot. In a fourth test, five apple orchards were monitored with groups of sex pheromone–baited traps placed either on the border or at three distances inside the orchards. The highest moth counts were in traps placed at the border, and the lowest moth counts were in traps placed 30 and 50 m from the border. In a fifth test, the proportion of traps failing to catch any moths despite the occurrence of local fruit injury was significantly higher in traps placed 50 versus 25 m from the border. The implications provided by these data for designing an effective monitoring program for codling moth in sex pheromone–treated orchards are discussed.

KEY WORDS *Cydia pomonella*, mating disruption, sex pheromone, monitoring

The adoption of sex pheromone–based technologies for the management of codling moth, *Cydia pomonella* L., in pome fruit orchards in western North America has been strongly influenced by growers' ability to acquire both reliable and timely data on this pest's population density. During the past four decades, capture of male codling moths in sex pheromone–baited traps have been the principal measure used to both trigger and time the use of insecticide sprays (Madsen and Vakenti 1973, Riedl et al. 1976). These traps continue to be widely used to monitor sex pheromone–treated orchards (Gut and Brunner 1996); however, several changes from their standard use in conventionally managed orchards have been required (Riedl et al. 1986). Codling moth within sex pheromone–treated orchards is typically monitored with a high-load lure to increase moth catch (Charmillot 1990). Traps are also placed high in the canopy (Knight 1995a) and away from sex pheromone dispensers (Knight et al. 1999). The recommended density of traps has been increased to one trap per hectacre (Gut and Brunner 1996). Improvements in trap design (Knight et al. 2002) and developments of new, long-lasting lures (Knight 2002) have also improved the effectiveness of monitoring codling moth in these orchards.

Standardization in trap and lure use has been suggested as a rational approach to reduce the variability in the performance of traps (Riedl 1980). Optimal trap and lure selection and proper seasonal maintenance are key factors allowing the establishment of meaningful action thresholds (Knight and Christianson 1999). Trap placement is one of these key factors. Trap height and orientation within the canopy of trees have been shown to be important factors influencing moth catch (Riedl et al. 1979, McNally and Barnes 1981). However, trap placement within the orchard has not been standardized in the development of action thresholds (Gut and Brunner 1996).

Several studies conducted in conventional orchards found that moth catch was several-fold higher in traps placed on the borders versus the interior of orchards (Madsen and Vakenti 1973, Westigard and Graves 1976). Thresholds were based on

[1] Corresponding author, e-mail: aknight@yarl.ars.usda.gov.

moth catches in the interior traps, but catches in border traps were used to assess whether male moths were immigrating into the orchard from outside sources and to recommend border spraying (Westigard and Graves 1976). High male counts in border-placed traps were typical, but whether these counts represented within-orchard or extra-orchard populations varied among sites (Madsen and Vakenti 1973, Westigard and Graves 1976).

Monitoring of codling moth in the early, large-scale trials of mating disruption in western North America typically used internal grids of traps (Knight 1995b, Judd et al. 1996, Gut and Brunner 1998). However, it is not clear if growers used mean moth catch per trap within the block or the highest counts per trap in deciding whether to apply supplemental insecticide sprays in these studies. Several more recent studies have relied solely on perimeter traps to monitor codling moth (Knight 2004, Knight and Light 2005a).

The higher labor cost, including increased monitoring associated with using sex pheromones to manage codling moth, has been identified as a significant factor that can reduce its adoption rate (Williamson et al. 1996). The speed of adoption of sex pheromones would likely increase if factors such as reliable monitoring could reduce the uncertainty (risk) associated with the effectiveness of this approach. Unfortunately, sex pheromone–baited traps often fail to catch moths despite the occurrence of fruit injury, termed "false-negative" catch (Knight and Light 2005b). The effect of trap placement within orchards on false-negative catches has not been previously examined. Further improvements in monitoring codling moth that could reduce the cost and minimize the risk of missing an incipient infestation within an orchard are especially needed.

Herein, five experiments are reported that either evaluated the capture of codling moths across the interface of adjacent sex pheromone–treated and –untreated orchard blocks or the influence of trap placement within sex pheromone–treated orchards in relation to the orchard's borders on moth catches. Together these data show the significant influence of a sex pheromone treatment on moth movement among orchard blocks and its potential impact on monitoring this key pest. Based on these studies, recommendations on implementing an effective monitoring program for codling moth in sex pheromone–treated orchards are presented.

Materials and Methods

Recapture of Sterilized Male and Female Moths. Two pairs of adjacent 0.2-ha plots were established in each of two pear, *Pyrus communis* L., and one apple, *Malus domestica* (Borkhausen), orchards in 1995 and in two apple and one pear orchards in 1996. All orchards were situated in the Yakima Valley (46°30′, 120°50′) east of either Moxee or Parker, WA, respectively. Apple orchards were planted with 'Delicious' and 'Golden Delicious', and pear orchards were planted with 'Bartlett' and D'Anjou'. Adjacent pairs of plots were oriented east–west in each orchard, and the position of the sex pheromone treatment was alternated in the two plots at each orchard. One plot within each pair was treated with sex pheromone dispensers, Isomate-C Plus dispensers (Pacific Biocontrol, Vancouver, WA), applied at a rate of 1,000 dispensers/ha, and the other plot was left untreated. Dispensers were loaded with 182.3 mg of a 60:33:7 blend of (*E, E*)-8–10-dodecadien-1-ol (codlemone), dodecan-1-ol, and tetradecan-1-ol. Treated and untreated plots were five rows by 12 trees. Tree and row spacing was 5 by 6 m. Plots were separated by one row designated as the "moth release row."

Three thousand sterilized moths were placed on the ground along the entire 60 m length of the moth release row in each pair of plots at the start of each test. Sterile codling moths (1:1 ratio of both sexes) were obtained from the codling moth mass-rearing Sterile Insect Release facility in Osoyoos, British Columbia, Canada. Moths were sterilized with gamma radiation (33 krad) from a Cobalt^{60} source (dose rate of 1,150–1,320 rad/min). Moths were kept chilled at 2–3°C for 12–36 h before field releases.

Pairs of clear plastic interception traps (0.1 m^2) coated with oil (STP Oil Treatment, STP, Ft. Lauderdale, FL) were placed on 15 trees spaced 12–15 m apart within each plot, starting on the second row (Weissling and Knight 1994). Interception traps were attached to clips with plastic strapping, and poles were used to attach traps to branches in the upper third of the canopy. Traps were replaced once 3–4 d after moth releases. Studies were conducted 7–14 and 18–25 July 1995 and 20–28 May and 3–10 June 1996. Moths were collected from traps and sexed in the laboratory. Sterilized moths were easily segregated from wild moths based on their pink gut colors caused by the incorporation of a red dye in the artificial diet at the SIR facility.

Trapping Wild Male and Female Moths. Interception traps were used to compare the distributions of natural populations of male and female codling moth within sex pheromone–treated and –untreated plots. Two sets of both treatments were established in two 'Delicious' apple orchards near Moxee, WA, in 1995, $n = 4$ replicates. Both orchards had >20% fruit injury from codling moth at harvest during the previous two seasons (unpublished data). Plots were 37 by 77 m or 11 rows by 15 trees. The physical border of the orchards served as one edge of each plot. The interior edge of each plot was adjacent to several hectares of untreated trees. Interception traps were placed on the border and the edge of each plot, as well as, on an interior row 24 m from the orchard's edge and another row 54 m from the edge of the orchard and 24 m from the interior edge of the plots. Plots within each orchard were separated by >50 m. Plots were oriented east–west in one orchard and north–south in the second orchard. The sex pheromone–treated plots were treated with Isomate-C Plus dispensers applied at 1,000 dispensers/ha. Traps were set out 11 May (10 d after the start of moth flight) and checked 7 d later. Moths were collected from traps and sexed in the laboratory. Female moths were dissected to determine their mating status.

Transect Studies. Studies were set up in two unsprayed 'Delicious' apple orchards situated within 0.3 km of each other near Moxee, WA. Tree-row spacing was 5 by 6 m in both orchards. Plots treated with Isomate-C Plus dispensers at a rate of 1,000/ha were established in the central area of each orchard. Treated plots were 50 trees × 17 rows. Two north–south transects of sticky wing-style traps (Trécé, Adair, OK) spaced 10 m apart were established starting 50 m north of the sex pheromone–treated area, running through the treated area, and extending 50 m south of the plot. Transects established in each orchard were with all traps baited with red rubber septa loaded with either 1.0 or 10.0 mg codlemone (Trécé). Transects were separated by 24 m. Traps were placed in the upper third of the canopy on all trees. New traps and lures were used on each date. Before each test, 10,000 sterilized codling moths were released uniformly throughout a 3.8-ha area (250 by 150 m) surrounding the treated plots and an additional 50-m buffer zone (eight rows or 10 trees) extending outside the treated plots. Sterilized moths from the SIR facility were kept chilled at 2°C and were released on the ground by a specialized hopper and blower unit mounted on the front of an all-terrain vehicle (McMechan and Proverbs 1972). Studies were repeated on four dates: 19–23 and 26–30 July and 4–8 and 11–15 August 1997. Wind direction was recorded every 5 min during a 3-h time period around dusk during each test with a cup anemometer (MetOne Instruments, Grants Pass, OR). Data were stored on a Campbell 21XL data logger (Campbell Scientific, Logan, UT) and summarized for each 15° starting from north (0°).

Trap Placement Near Orchard Borders. Studies were conducted in five 16-ha apple orchards situated within a 6-km^2 area near Brewster, WA (48° N, 119° W) during 1998. Orchards included both 'Granny Smith' (three) and 'Fuji' (two) apples with tree-row spacing from 3.3 by 4.0 m to 4.0 by 5.3 m. All orchards were treated with 500–750 Isomate-C Plus dispensers/ha. All orchards were planted in either a north–south or east–west row orientation. The topography of orchards ranged from flat to a 3° slope from north to south. Wind direction was recorded as previously described. Sticky wing traps baited with a high-load Megalure dispenser (Trécé) were placed either on the edge tree or on trees 10, 30, and 50 m from the edge. Traps placed on the edge tree were hung in the interior perimeter of the canopy, <3 m from the outside edge of the orchard. All traps were attached to poles and hung in the upper third of the canopy. Mean tree height in orchards ranged from 3.8 to 4.8 m. One trap at each distance from the border was placed on each of the four sides of orchards. The order of treatments was randomized on each side of the orchard. Initially, traps were placed on rows of trees spaced 30–35 m apart; however, in some cases, trap position had to be adjusted to ensure that traps placed near the corners of orchards were >30 m apart. Traps were placed in orchards on 21 April and checked every 6–8 d until 18 August. A final trap check was conducted on 19 September. Moth counts per trap were summarized over the entire season.

Trap Placement and Detection of Fruit Injury. Studies were conducted in 1999 and 2000 to evaluate the effectiveness of sex pheromone–baited traps to reflect the occurrence of fruit injury. Studies were conducted in 80 apple orchards (8–16 ha) situated near Brewster, WA. Orchards were comprised of five cultivars: 'Granny Smith', 'Fuji', 'Delicious', 'Golden Delicious', and 'Gala'. All orchards were treated with Isomate-C Plus dispensers applied at rates of 500–1,000 dispensers/ha. Delta-shaped traps baited with Megalure dispensers were placed in orchards either 25 or 50 m from the physical border of the orchard. Traps were positioned on the western edge of plots and were spaced 100–150 m apart. Traps during both years were placed in orchards before 5 May and were checked each week until mid-September. Lures were changed after 8 wk, and sticky inserts were replaced when >20 cumulative moths were caught. Fruit injury was assessed in September by visually inspecting 30 fruits from 20 randomly selected trees situated <25 m from each trap. Only moth catch data from plots with fruit injury were summarized.

Statistical Analysis. All statistical analyses were performed with Statistix version 8 (Analytical Software 2003). Count data were transformed with $\log(y + 1)$ before analysis of variance (ANOVA). Recaptures of sterile male and female moths on interception traps were analyzed as a three-way ANOVA with treatment (sex pheromone or untreated), plot orientation (east or west), and crop (apple and pear) as factors. Captures of wild male and female moths on interception traps placed in adjacent sex pheromone–treated and –untreated plots were analyzed as a two-way ANOVA with treatment (sex pheromone and untreated) and trap row position as main factors. The proportion of female moths that were mated was transformed with arcsine (sqrt y) and analyzed with a one-way ANOVA. A univariate repeated-measures ANOVA (date was the within subject factor) was used to compare moth catches at 21 transect positions in traps baited with either 1- or 10-mg codlemone lures. The distributions of moths in transects of traps baited with the two lure types were compared with a two-tailed Kolmogorov-Smirnov (K-S) test using Smirnov's χ^2 approximation (Analytical Software 2003). A two-way ANOVA was used to test the effect of distance from the border and cardinal direction on sex pheromone–baited traps. Fruit injury data were converted to proportions and transformed with arcsine (sqrt y) before ANOVA. Fisher exact test was used to compare the failure of traps placed either 10 or 50 m from the border of orchards to detect fruit injury. Interaction terms were included in all two- and three-way ANOVA models. Means were separated in significant ANOVAs with a Tukey's pairwise comparison test.

Table 1. Recapture of sterilized codling moths on clear, oil-coated interception traps after releases along a row situated between adjacent plots treated with either Isomate-C Plus dispensers or left untreated in apple and pear orchards during 1995–1996 (n = 12)

Treatment	Mean (SE) no. recaptured per interception trap	
	Males	Females
Sex pheromone	14.3 (4.2)	1.1 (0.3)
Untreated	4.3 (1.3)	1.8 (0.6)
Model factors (df = 1,16)	Three-way ANOVA	
Treatment	$F = 5.84, P = 0.03$	$F = 1.50, P = 0.24$
Plot orientation (E, W)	$F = 0.81, P = 0.38$	$F = 2.75, P = 0.11$
Crop (apple, pear)	$F = 0.15, P = 0.70$	$F = 0.67, P = 0.42$
Treat × orientation	$F = 0.48, P = 0.50$	$F = 0.67, P = 0.42$
Treat × crop	$F = 0.03, P = 0.86$	$F = 0.08, P = 0.78$
Orientation × crop	$F = 0.64, P = 0.43$	$F = 2.95, P = 0.11$
Treatment × orientation × crop	$F = 0.00, P = 0.99$	$F = 0.15, P = 0.70$

Results

Recapture of Sterilized Male and Female Moths. Significant differences occurred in the recapture of sterilized male moths on interception traps between sex pheromone–treated and –untreated plots (Table 1). Approximately three times more male moths were recaptured in the sex pheromone than in the untreated plots. The recapture of female moths, however, did not differ between plots. The numbers of female versus male moths were significantly lower in both the sex pheromone ($t = 4.78$, df = 11, $P < 0.001$) and untreated plots ($t = 2.30$, df = 11, $P = 0.04$). The effects of plot orientation (east versus west) and crop effects (apple versus pear) and two- and three-way interactions were not significant in tests with either male or female moths (Table 1).

Trapping Male and Female Moths. Significantly more male and female moths were caught on interception traps placed in the sex pheromone–treated than in untreated plots established in two heavily infested orchards (Table 2). Trap position was a significant factor affecting male moth catches, primarily because of a two-fold increase in captures in traps placed along the interior border of sex pheromone–treated plots. Trap position was not a significant factor for female moth catch. The interaction of treatment and trap position was also not significant (Table 2).

A significantly higher mean proportion of female moths was mated within the untreated (0.66 ± 0.07 [SE]) versus the sex pheromone–treated plots (0.49 ± 0.05; $F = 10.74$; df = 1,24; $P < 0.01$). Trap position was not a significant factor affecting mating status ($F = 0.22$; df = 3,24; $P = 0.88$), nor was the interaction of treatment and trap position significant ($F = 1.35$; df = 3,24; $P = 0.28$).

Transect Studies. The distribution of moth catches was similar among traps baited with either a 1.0- or 10.0-mg sex pheromone lure (two-tailed K-S test, $P = 0.23$). Wind was recorded from all directions during these tests; however, wind was predominantly (45%) from 300 (NW) to 30° (NNE). Significant differences occurred among moth catches in transects of traps baited with both 1.0- ($F = 13.73$; df = 20,21; $P < 0.0001$) and 10.0-mg ($F = 11.28$; df = 20,21; $P < 0.0001$) sex pheromone lures (Fig. 1).

The highest moth catches with both lures occurred outside the sex pheromone–treated plots. The one exception was for traps placed on the upwind border of the treated plots. Traps in this position caught significantly more moths than traps placed inside and 10–50 m from the borders of the treated plots. Traps baited with a 1-mg lure and placed inside and 10 m from the upwind edge of treated plots caught similar numbers of moths as traps situated 10–30 m outside and upwind from the treated plots (Fig. 1A).

Traps placed at the downwind border of the treated plot caught similar numbers of moths as traps within the plot and significantly fewer moths than traps placed downwind, except for 1.0-mg traps at 10 and 20 m (Fig. 1A and B). Moth catches in traps placed 10 and 20 m outside and downwind of the treated plots were significantly lower than in traps placed outside and >30 m upwind of the treated plots. Moth catches in traps placed >30 m upwind or downwind of the treated plots were generally not significantly different.

Trap Placement Near Orchard Borders. Significant differences in moth catches occurred among sex pheromone–baited traps because of both trap distance from the border and the primary cardinal direction of the orchard's edge (Table 3). Moth catches were highest in traps placed on the border and were significantly different from catches in traps placed at 30 or 50 m but

Table 2. Mean (SE) captures of male and female codling moth on clear, oil-coated interception traps placed in sex pheromone–treated and –untreated apple plots in 1995 (n = 4)

Trap placement	Male moths		Female moths	
	Sex pheromone	Untreated	Sex pheromone	Untreated
Orchard edge	10.4 (0.8)b	6.3 (1.8)b	5.8 (1.6)	2.5 (0.7)
Interior[a]	9.6 (2.1)b	5.8 (1.6)b	4.5 (1.5)	3.4 (0.5)
Interior[b]	14.8 (2.9)ab	6.4 (1.6)ab	5.4 (1.4)	3.0 (0.8)
Interior border	26.0 (6.5)a	7.4 (0.5)a	5.7 (1.0)	4.4 (1.3)
ANOVA				
Treatment	$F_{1, 24} = 24.93, P < 0.0001$		$F_{1, 24} = 4.96, P = 0.04$	
Placement	$F_{3, 24} = 3.28, P = 0.04$		$F_{3, 24} = 0.46, P = 0.71$	
Treatment × placement	$F_{3, 24} = 0.94, P = 0.44$		$F_{3, 24} = 0.45, P = 0.72$	

Column means followed by different lowercase letters were significantly different, Tukey's test ($P < 0.05$).
[a] Interception traps were placed in a row 24 m from the edge of the orchard.
[b] Interception traps were placed 54 m from the edge of the orchard and 24 m from the interior border of the plot.

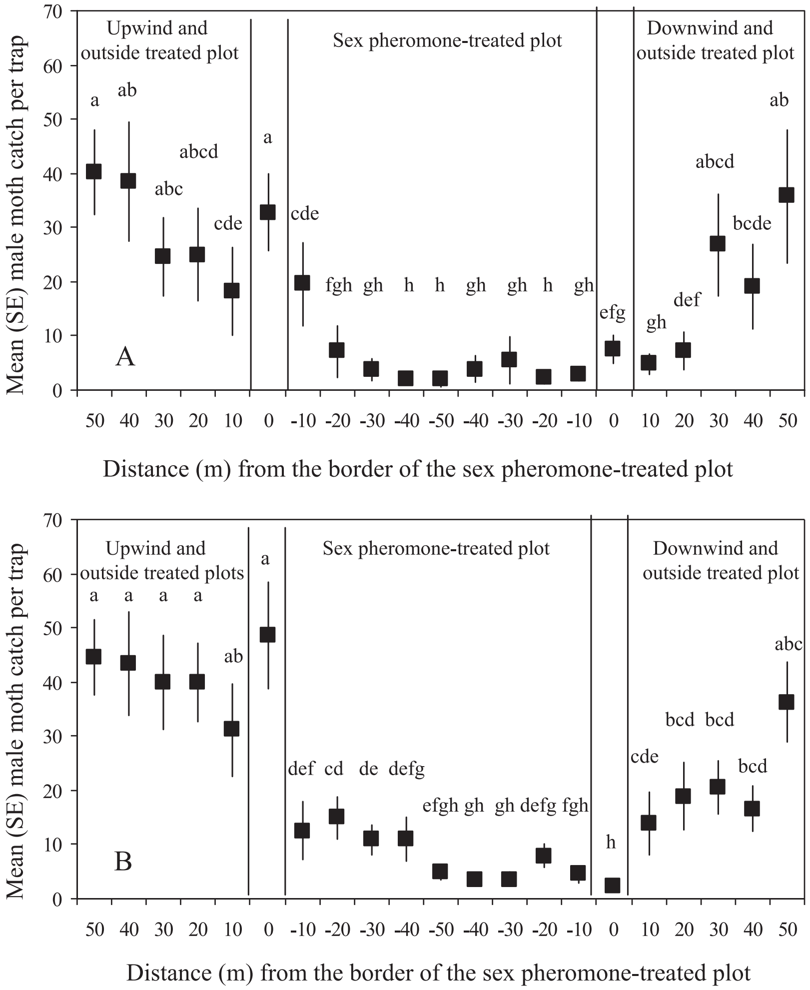

Fig. 1. Mean ± SE recaptures of sterilized male codling moths in traps spaced every 10 m in transects beginning 50 m upwind from plots treated with sex pheromone dispensers to 50 m downwind of these plots. Traps were baited with red rubber septa loaded with either 1 (A) or 10 mg (B) codlemone. Studies were conducted in two orchards with two transects of each lure type on 26 July and 8 August 1997. Means with same letters are not significantly different, $P > 0.05$.

not 10 m from the border. Traps at 10 m caught similar numbers of moths as traps placed 50 m from the border. Traps at 30 and 50 m caught similar numbers of moths.

The predominant quadrant for wind direction during dusk (61%) in the Brewster orchards was from the west (270°) to north (360°). Moth catches were similar on the west and northern sides of orchards (Table 3). An intermediate number of moths was caught in traps placed on the eastern edge of orchards. Traps placed on the southern edge of orchards caught significantly

Table 3. Comparison of male codling moth catches in sex pheromone–baited traps placed at different distances from the physical border of apple orchards treated with sex pheromone dispensers, 1998 ($n = 5$)

Trap distance (m) from orchard border	Mean (SE) male moth catch	Direction of orchard edge	Mean (SE) male moth catch
Edge tree	9.2 (5.4)a	North	5.0 (1.6)a
10	4.2 (1.4)ab	West	10.1 (5.5)a
30	2.3 (1.4)c	South	0.8 (0.3)b
50	2.7 (1.6)bc	East	2.5 (1.1)ab
Two-way ANOVA	$F_{3, 64} = 2.88$, $P = 0.04$		$F_{3, 64} = 3.17$, $P = 0.03$

Column means followed by a different letter were significantly different, Tukey's test ($P < 0.05$). Interaction of distance and direction was not significant ($F_{9, 64} = 0.23$, $P = 0.99$).

Table 4. Mean male codling moth catches in sex pheromone–baited traps and mean percent fruit injury surrounding each trap in orchards monitored in 1999–2000 with fruit injury (n = 80)

Distance (m) from border	Injury with no moth catch		Injury with moth catch		
	No. traps	Mean (SE) percent injury	No. traps	Mean (SE) catch per trap	Mean (SE) percent fruit injury
25	1	0.33	24	11.5 (3.1)	1.8 (0.6)
50	8	0.44 (0.19)	17	6.5 (1.7)	1.0 (0.3)
ANOVA				$F_{1,\,39} = 1.26$, $P = 0.27$	$F_{1,\,39} = 1.43$, $P = 0.24$

fewer moths than traps at either the western or northern edge of orchards.

Trap Placement and Detection of Fruit Injury. Fruit injury from codling moth was detected in only 25 of the 80 plots surrounding both the border and interior traps, respectively. A significantly higher proportion of traps placed at 50 versus 25 m from the border failed to catch moths (0.32 versus 0.04), despite the occurrence of surrounding fruit injury (Fishers exact test, $P = 0.02$). Mean moth catch and the surrounding mean percent fruit injury were nearly twice as high for traps placed at 25 versus 50 m from the border of orchards, but these were not statistically different (Table 4). Mean percent fruit injury surrounding traps at 50 m from the border was not significantly different regardless of whether traps caught moths ($F = 2.21$; df = 1,23; $P = 0.15$).

Discussion

The placement of traps within apple and pear orchards can have a significant influence on the numbers of codling moths captured. Studies reported here focused both on the movement of moths toward and within plots treated with sex pheromone dispensers (Isomate-C Plus) using sterilized, laboratory-reared, and wild moths. Male moths moved toward sex pheromone–treated plots and were caught at their highest numbers at the interface of treated and untreated plots. Conversely, female moths did not move toward plots treated with sex pheromone. Catches of both sexes, however, were higher within treated versus untreated plots, suggesting that the general movement of moths may be higher in the presence of sex pheromone.

The potential influence of sex pheromone on female moth behavior is poorly understood. Antennae of both mated and virgin female moths can detect sex pheromone (Barnes et al. 1992, De Cristofaro et al. 2004). Weissling and Knight (1996) found that the presence of sex pheromone in moving air increased the calling frequency of virgin females under laboratory conditions. In the field, Weissling and Knight (1995) found that laboratory-reared female moths did not shift their vertical distribution in trees in response to the height of Isomate-C dispensers. Unfortunately, it is not possible to assign the higher catches of wild female moths captured in sex pheromone–treated versus untreated plots to a specific behavioral effect. Moth catches on the unbaited interception trap are thought to reflect levels of moth activity (Weissling and Knight 1994). It is interesting, therefore, that the lower catch in the untreated plots was associated with a higher proportion of mated versus virgin females. Mated female codling moths have a lower flight capacity than virgin females because of depletion in energy reserves (Schumacher et al. 1997). Unfortunately, the diel circadian activities of virgin female moths in the field have not been well studied.

The interception trap has been useful in the comparison of population densities of male and female moths at the border versus the center of orchards (Knight 2000). Data on the mating status of female moths have also been collected with these traps, including the mean numbers of eggs per mated female. More recently, the densities and mating status of female codling moths have been measured with sticky traps baited with the pear ester, (*E,Z*)-2,4-decadienoate (Light et al. 2001). Interception traps baited with pear ester caught nine-fold more female moths than a similarly baited delta-shaped trap (unpublished data). As a result, the development of an effective bisexual "lure and kill" strategy for codling moth has focused on the use of insecticide-treated vertical surfaces baited with a combination of sex pheromone and pear ester (Knight 2005).

Higher catches of male codling moth in border sex pheromone traps have been reported previously from both conventional (Westigard and Graves 1976) and sex pheromone–treated orchards (Knight 2000). The influences of wind direction and orchard topography are likely important factors influencing the performance of sex pheromone–baited traps (Riedl et al. 1986). For example, data in 1998 were affected by both of these factors, because traps catching the greatest numbers of moths were also positioned upwind (NW–N) and higher on the prevailing 3° north–south slope within orchards.

The consistently higher male moth catches at the upwind borders of the sex pheromone–treated orchards were also likely affected by the clearer signal emitted by the sex pheromone lure within the trap. Milli et al. (1997), using a portable electroantennographic device, measured a depletion of sex pheromone in a band extending 15 m from the upwind edge of a treated apple orchard. They also found that the concentration of sex pheromone at a similar order of magnitude from the treated plots extended as far as 60 m downwind. Moth catch data collected during the 1997 transect studies were consistent with this pheromone plume model.

The distribution of male moth catches reported here is also consistent with the visual observations of codling moth made by Witzgall et al. (1999). They reported that male flights within canopies and along tree rows were elevated in the presence of sex pheromone. Male moths from nearby untreated orchards were observed to fly toward sex pheromone–treated blocks. Unfortunately, these data are likely biased for moths seen silhouetted above the tops of canopies versus moths moving within the canopy. Weissling and Knight (1995) used fluorescent powder and a black light to detect the location of nonflying moths within the tree canopy 2 h after dusk. The mean vertical distribution of male moths was shifted lower in the canopy by placing sex pheromone dispensers at 2 versus 4 m in the trees.

These results have several implications for improved management of codling moth. The different responses of male and female codling moths to sex pheromone and the modulating influences of wind and topography can create disparate correlations of male catches and female moth densities within and among different orchards. Pest managers have tried to reduce this uncertainty by using a high-density grid of traps. However, effective management of codling moth requires knowledge of its population density both within the orchard and in surrounding orchards. For example, Knight et al. (1995) showed that codling moth fruit injury spread up to 350 m into a previously clean orchard from a neighboring infested orchard between summer generations. In contrast, border traps can also overestimate the movement of female moths into orchards (Madsen and Vakenti 1973).

Several improvements can be made to the current monitoring approach for codling moth. First, a protocol is needed that explicitly considers trap placement within orchards and considers the influences of wind direction and orchard topography. Action thresholds would need to be established for specific trap positions. Because traps placed on the border of orchards are most likely to overestimate the pest pressure within the orchard, an area-wide program where growers would together implement an interorchard monitoring program could be useful (Knight 1999).

Second, instead of using border traps, growers could place their perimeter traps 10–30 m from the border. Traps placed at this location were shown to be effective in catching moths, detecting fruit injury, and were not strongly impacted by wind direction. Interior traps placed at 50 m caught low numbers of moths, likely because of both the disruption of traps by sex pheromone dispensers (Milli et al. 1997) and the lower moth density in these areas of the orchards (Knight 2000). Nearly 30% of interior traps failed to detect local fruit injury. Thus, the density of interior traps could be reduced in most orchards, unless there is a suspected interior pest problem.

A third improvement may be to monitor codling moth with traps baited with pear ester. Pear ester lures have been effective in both establishing the start of moth flight (Knight and Light 2005c) and action thresholds based on cumulative catches of male and female moths (Knight and Light 2005b). Many factors can influence the performance of pear ester–baited traps, including crop, cultivar, and position of the trap within the canopy (Knight and Light 2005a). A standardized protocol with these traps has been presented using only perimeter traps placed 25 m from the borders (Knight and Light 2005c). The use of an alternating grid of pear ester– and sex pheromone–baited traps has been suggested for growers initially adopting this new technology (Knight et al. 2006). Pear ester lures may be particularly useful to monitor problem areas within orchards where sex pheromone–baited traps have previously failed to detect fruit injury and to detect female moth immigration from neighboring orchards or infested bin piles (Higbee et al. 2001).

Acknowledgments

I thank K. Johnson, J. Turner, B. Christianson, and D. Larson, USDA–ARS, Wapato, WA, for help in setting up the field trials and M. and T. Goehry, Brewster, WA, for collecting the field data. T. Weissling, University of Nebraska, Lincoln, NE, set up and collected data from grids of interception traps placed in the Moxee orchard during 1995. P. Garza, Manzana Orchards, Moxee, WA, and T. Pitts, Gebbers Farms, Brewster, WA, graciously offered orchards in this study. D. Horton and W. Yee, USDA–ARS, Wapato, WA; D. Johnson, University of Arkansas, Fayetteville, AR; H. Hogmire, WV University, Kearneysville, WV; and A. Agnello, Cornell University, Geneva, NY, provided helpful reviews of an earlier version of this paper. This research was partially funded by the Washington Tree Fruit Research Commission, Wenatchee, WA.

References Cited

Analytical Software. 2003. Statistix 8. Analytical Software, Tallahassee, FL.

Barnes, M. M., J. G. Millar, P. A. Kirsch, and D. C. Hawks. 1992. Codling moth (Lepidoptera: Tortricidae) control by dissemination of synthetic female sex pheromone. J. Econ. Entomol. 85: 1274–1277.

Charmillot, P. J. 1990. Mating disruption technique to control codling moth in Western Switzerland, pp. 165–182. *In* R. L. Ridgway, R. M. Silverstein, and M. N. Inscoe (eds.), Behavior-modifying chemicals for insect pest management. Marcel Dekker, New York.

De Cristofaro, A., C. Ioriatti, F. Molinari, E. Pasqualini, G. Anfora, G. S. Germinara, M. Villa, and G. Rotundo. 2004. Electrophysiological responses of codling moth, *Cydia pomonella* (L.) (Lepidoptera: Tortricidae), to codlemone and pear ester ethyl (*E*, *Z*)-2,4-decadienoate: peripheral interactions in their perception and evidences for cells responding to both compounds. Bull. Insect. 57: 1–8.

Gut, L. J., and J. F. Brunner. 1996. Implementing codling moth mating disruption in Washington pome fruit orchards. Washington State University, Wenatchee, WA.

Gut, L. J., and J. F. Brunner. 1998. Pheromone-based management of codling moth (Lepidoptera: Tortricidae) in Washington apple orchards. J. Agric. Entomol. 15: 387–405.

Higbee, B. S., C. O. Calkins, and C. A. Temple. 2001. Overwintering of codling moth (Lepidoptera: Tortricidae) larvae in apple harvest bins and subsequent moth emergence. J. Econ. Entomol. 94: 1511–1517.

Judd, G., M. Gardiner, and D. Thomson. 1996. Commercial trials of pheromone- mediated mating disruption with Isomate-C to control codling moth in British Columbia apple and pear orchards. J. Entomol. Soc. Br. Columbia. 93: 23–34.

Knight, A. L. 1995a. Evaluating pheromone emission rate and blend in disrupting sexual communication of codling moth (Lepidoptera: Tortricidae). Environ. Entomol. 24: 1396–1403.

Knight, A. L. 1995b. The impact of codling moth (Lepidoptera: Tortricidae) mating disruption on apple pest management in Yakima Valley, Washington. J. Entomol. Soc. Br. Columbia. 92: 29–38.

Knight, A. L. 1999. Spatial versus sociological-based pest management: biological and economic constraints. Proc. Wash. Hort. Assoc. 95: 161–166.

Knight, A. L. 2000. Monitoring codling moth (Lepidoptera: Tortricidae) with passive interception traps in sex pheromone-treated apple orchards. J. Econ. Entomol. 93: 1744–1751.

Knight, A. L. 2002. A comparison of gray halo-butyl elastomer and red rubber septa to monitor codling moth (Lepidoptera: Tortricidae) in sex pheromone-treated orchards. J. Entomol. Soc. Br. Columbia 99: 123–132.

Knight, A. L. 2004. Managing codling moth (Lepidoptera: Tortricidae) with an internal grid of either aerosol puffers or dispenser clusters plus border applications of individual dispensers. J. Entomol. Soc. Br. Columbia 101: 69–77.

Knight, A. L. 2005. The addition of the pear ester to improve insecticidal control of codling moth. Proceedings of the Western Orchard Pest and Disease Management Conference, 5–7 January 2005, Portland, OR.

Knight, A., and B. Christianson. 1999. Using traps and lures in pheromone-treated orchards. Good Fruit Grower. 50: 45–51.

Knight, A. L., and D. M. Light. 2005a. Factors affecting the differential capture of male and female codling moth (Lepidoptera: Tortricidae) in traps baited with ethyl (*E,Z*)-2,4-decadienoate. Environ. Entomol. 34: 1161–1169.

Knight, A. L., and D. M. Light. 2005b. Developing action thresholds for codling moth (Lepidoptera: Tortricidae) with pear ester- and codlemone-baited traps in apple orchards treated with sex pheromone mating disruption. Can. Entomol. 137: 739–747.

Knight, A. L., and D. M. Light. 2005c. Timing of egg hatch by early-season codling moth (Lepidoptera: Tortricidae) predicted by moth catch in pear ester- and codlemone-baited traps. Can. Entomol. 137: 728–738.

Knight, A. L., J. F. Howell, L. M. McDonough, and M. Weiss. 1995. Mating disruption of codling moth (Lepidoptera: Tortricidae) with polyethylene tube dispensers: determining emission rates and the distribution of fruit injuries. J. Agric. Entomol. 12: 85–100.

Knight, A. L., B. A. Croft, and K. A. Bloem. 1999. Effect of mating disruption dispenser placement on trap performance for monitoring codling moth (Lepidoptera: Tortricidae). J. Entomol. Soc. Br. Columbia 96: 95–102.

Knight, A. L., D. Larson, and B. Christianson. 2002. Flight tunnel and field evaluations of sticky traps for monitoring codling moth (Lepidoptera: Tortricidae) in sex pheromone-treated orchards. J. Entomol. Soc. Br. Columbia. 99: 107–116.

Knight, A., R. Hilton, P. Van Buskirk, and D. Light. 2006. Using pear ester to monitor codling moth in sex-pheromone-treated orchards. Oregon State University Extension Service, Corvallis, OR.

Light, D. M., A. L. Knight, C. A. Henrick, D. Rajapaska, B. Lingren, J. C. Dickens, K. M. Reynolds, R. G. Buttery, G. Merrill, J. Roitman, and B. C. Campbell. 2001. A pear-derived kairomone with pheromonal potency that attracts male and female codling moth, *Cydia pomonella* (L.). Naturwissenschaften 88: 333–338.

Madsen, H. F., and J. M. Vakenti. 1973. Codling moth: use of codlemone-baited traps and visual detection of entries to determine need of sprays. Environ. Entomol. 2: 677–679.

McMechan, A. D., and M. D. Proverbs. 1972. Equipment and procedures for release of sterile codling moths. Can. Agric. Engineer. 14: 42–45.

McNally, P. S., and M. M. Barnes. 1981. Effects of codling moth pheromone trap placement, orientation and density on trap catches. Environ. Entomol. 10: 22–26.

Milli, R., U. T. Koch, and J. J. de Kramer. 1997. EAG measurements of pheromone distribution in apple orchards treated for mating disruption of *Cydia pomonella.* Entomol. Exp. Appl. 82: 289–297.

Riedl, H. 1980. The importance of pheromone trap density and trap maintenance for the development of standardized monitoring procedures for the codling moth (Lepidoptera: Tortricidae). Can. Entomol. 112: 529–544.

Riedl, H., B. A. Croft, and A. J. Howitt. 1976. Forecasting codling moth phenology based on pheromone trap catches and physiological time models. Can. Entomol. 108: 449–460.

Riedl, H., S. A. Hoying, W. W. Barnett, and J. E. DeTar. 1979. Relationship of within-tree placement of the pheromone trap to codling moth catches. Environ. Entomol. 8: 765–769.

Riedl, H., J. F. Howell, P. S. McNally, and P. H. Westigard. 1986. Codling moth management: use and standardization of pheromone trapping systems. University of California Division of Agriculture and Natural Resources, Oakland, CA.

Schumacher, P., A. Weyeneth, D. C. Weber, and S. Dorn. 1997. Long flights in *Cydia pomonella* L. (Lepidoptera: Tortricidae) measured by a flight mill: influence of sex, mated status, and age. Physiol. Entomol. 22: 149–160.

Weissling, T. J., and A. L. Knight. 1994. Passive trap for monitoring codling moth (Lepidoptera: Tortricidae) flight activity. J. Econ. Entomol. 87: 103–107.

Weissling, T. J., and A. L. Knight. 1995. Vertical distribution of codling moth in pheromone-treated and untreated plots. Entomol. Exp. Appl. 77: 271–275.

Weissling, T. J., and A. L. Knight. 1996. Oviposition and calling behavior of codling moth (Lepidoptera: Tortricidae) in the presence of codlemone. Ann. Entomol. Soc. Am. 89: 142–147.

Westigard, P. H., and K. L. Graves. 1976. Evaluation of pheromone baited traps in a pest management program on pears for codling moth control. Can. Entomol. 108: 379–382.

Williamson, E. R., R. J. Folwell, A. Knight, and J. F. Howell. 1996. Economics of employing pheromones for mating disruption of the codling moth, *Carpocapsa pomonella.* Crop Protect. 15: 473–477.

Witzgall, P., A.-C. Bäckman, M. Svensson, U. T. Koch, F. Rama, A. El-Sayed, J. Brauchi, H. Arn, M. Bengtsson, and J. Löfqvist. 1999. Behavioral observations of codling moth, *Cydia pomonella,* in orchards permeated with synthetic pheromone. Biocontrol 44: 211–237.

Received for publication 7 April 2006; accepted 17 November 2006.